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AIR BREATHING PROPULSION IN AEROSPACE TRANSPORT

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ICAS Paper No.66-28

AIR BREATHING PROPULSION IN AEROSPACE TRANSPORT /i**

J.Dupin*

The French turbofan-ramjet engine by Nord-Aviation, with lox injection at the end of the climb phase, to be used as the first stage of a space transport or a launch vehicle, is described in some detail, with sketches of the composite engine and performance diagrams at various Mach numbers. Advantages of airbreathers over conventional ballistic launch vehicles are given, including low specific fuel consumption on return to subsonic flight and in cruising, adaptability to variations in Mach by use of either air bypass, reduction in engine weight by use of liquid oxygen for thrust augmentation, etc. Air rates of flow superior to the American Mach 3 SST or the B70 are expected by using a maximum air-inlet cross section adapted to Mach 3.7 - 4. Structural use of refractory metal sandwich composites, including Réné 41, molybdenum, niobium, and tantalum, for temperatures to 1600°C as tested in stages of the Diamant, Coralie, Europa vehicles and the Transall and Griffon aircraft, is discussed briefly.

The efficacy of using the atmosphere for propulsion is bound to the selection of the acceleration phase. For rocket engines, this leads to requirements that basically concern performance, kinetic heating, and structural lightness.

A propulsive unit, combining a ramjet and turbofan, making use of oxygen injection for certain phases of flight, satisfies these particular conditions.

The structure of such a unit is preferably composed of sandwich elements, produced from thin sheets of welded refractory alloys.

The main problems encountered in the development of such a propulsive unit are reviewed in this article, so as to demonstrate that a solution is possible within the framework of the present state of the art.

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Numerous studies have been made in recent years on the use of air-breathing engines for launch vehicles. We do not have in mind to give a general review of such vehicles nor to discuss the justification of conclusions drawn with

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** Numbers given in the margin indicate pagination in the original foreign text.

respect to their technical or economical interest. In fact, many of such investigations have been based on hypotheses which might appear quite promising but are too far from present-day practical experience to permit a reliable evaluation of either weight or performance estimates or of cost price and development expenditure.

In any case, it is difficult to present a comprehensive project so long as one does not know the space program or programs in which such vehicles are to be used. A fortiori, in the absence of such data, it is entirely illusory to establish a reliable cost balance for such an enterprise and thus to evaluate the cost of each individual mission in comparison with the conventional launching modes. /1

Conversely, it is impossible for space agency authorities to make their own plans for utilization of this particular mode of propulsion and to establish programs so long as they are not in possession of sufficiently reliable data in matters of performance and time schedules.

This constitutes a vicious circle and we are not pretending to give a ready way out of such a circle.

Our contribution merely has the purpose of demonstrating that, on the basis of acquired technology or of development in progress, it is possible to define and to produce an air-breathing propulsion unit for a launch vehicle whose performance and development or production time schedule can already be estimated with a good chance for success.

The choice of technical solutions proposed for reaching this goal may appear somewhat tentative in the eyes of some people, but we believe it necessary to adhere to this realistic viewpoint so as to give substance to the interest that space-program developers should have in the air-breathing engine configuration.

Although the advantages offered by utilizing the atmosphere for the first stage of a launch vehicle are well known, let us here review the most important ones.

Primarily, with respect to launch vehicles of the ballistic type, this consists in a simplification of the infrastructure of launching which becomes close to that used in conventional heavy aircraft.

Reentry is also facilitated, since the type of manned vehicle proposed here as well as its propulsion can be used either for subsonic or for supersonic flight. Therefore, it is easy for such a vehicle to return to its base, i.e., to a normally equipped landing field. /2

A large variety of orbital plans can be worked out because of a certain freedom of choice in the latitude of launching: The launch vehicle can actually cruise at subsonic speed to distances far from its base, followed by a steep accelerated climb after refueling in flight. In addition, the much greater flexibility of flight plan considerably facilitates rendezvous maneuvers, specifically with a satellite of any orbit.

Finally, it is obviously possible to profit from the high specific impulse of air-breathing engines.

It is no more than just to give also a few of the drawbacks, such as high structural weight, necessity of a landing gear and - more generally - necessity of life-support equipment required by the presence of a human pilot, difficulty of integration of the upper stages into the composite unit, problem of stage separation in the presence of high aerodynamic forces.

Nevertheless, none of these difficulties seems unsurmountable, and the advantages by far outweigh all drawbacks.

The larger portion of studies already made or still in progress in the field of interest here has the purpose of making the fullest possible use of the theoretical advantages of air-breathing propulsion and of obtaining masses, for insertion into orbit, more than 10% of those at liftoff. However, these same investigations also show the enormous scope of technical and technological problems that must be solved before arriving at this point, thus even placing the practical feasibility of the proposed system in jeopardy. Fortunately, it is possible to greatly reduce the volume of these problems, provided that some of the overall performance requirements are reduced. In any case, the performance will still remain better than that of conventional rocket launching vehicles. In addition, the extreme flexibility of use, obtained with air-breathing launch vehicles, constitutes a great advantage.

The mission of an air-breathing first stage is to carry the next stage /3
to a given altitude at a velocity predetermined in magnitude and direction, in accordance with an optimization study made for all stages. Depending on the selected trajectory for realizing this mission, the fuel weight and construction weight will differ. Therefore, it is necessary to search for the most efficient trajectories, i.e., for flight paths permitting attainment of the optimum mass ratio. We should recall here the basic limitations placed on atmospheric flight, shown in Fig.1 in plots of altitude versus Mach number.

Primarily, there is the noise produced at ground level, specifically on passing the sound barrier. The three curves, corresponding to induced pressures of 1 psf, 2 psf, and 2.5 psf, are those given for the supersonic transport. It is obvious that, for an air-breathing launch vehicle, noise intensities greater than those tolerated for the SST can be permitted; however, the configuration of the launch vehicle is aerodynamically much less favorable than that of the SST and it is most likely that the altitudes of passing through the sonic barrier will not be too different.

A second limitation is presented by the dynamic pressure whose role is essential in flutter phenomena and which constitutes a basic factor of the structural weight. The curves are plotted for 600, 700, and 800 knots.

At high velocities, the kinetic heating becomes a factor. This heating is especially pronounced at the leading edges that are amenable to a specific treatment but is less extensive in the other portions of the structure. The curves, corresponding to the pressure side of the wing assembly, are given for 950° and 1150°K.

The possibility of evolution in altitude is characterized by the curves /4 $\frac{nP}{SC_L}$ where n is the load factor, $\frac{P}{S}$ the net load, and C_L the lift coefficient. This limitation is important since it concerns the end of the trajectory which constitutes a means for giving the desired inclination to the velocity vector.

Finally, we should mention here that the first stage must be of sufficiently large size to permit integration of the upper stages which, in turn, means that the separation velocity must be high so that the launching process will be sufficiently economical.

So far as the structure of the engines themselves is concerned which, as will be shown in detail below, are of necessity composites of turbofans and ramjets, there exist certain limitations that are basically due to the fact that the air has been decelerated to subsonic velocity. At the dynamic pressure of constant flight, the internal pressure increases with the Mach number. The plotted curves correspond to internal pressures of 4, 6, and 8 atm.

Otherwise, the temperature of the air entering the engine itself is practically that of the overall temperature of flight, much higher than the temperature of the outer structure where the effects of conductivity of the boundary layer and radiation toward the outside have an influence. The plotted curves correspond to temperatures of 1000, 1500, and 2000°K. The acceptance of high values for the two quantities, pressure and temperature, results in an aggravation of the difficulties in designing the structure of the engine which invariably, provided that these difficulties are surmountable, leads to an increase in weight. These limitations, appearing at high Mach number, have to do mainly with the walls of the air bypass of the ramjet. It is well possible that limitations of internal pressure exist for the turbofan at low altitudes, but /5 these are probably compensated by the requirements due to passage through the sonic barrier.

From the viewpoint of performance, the problem appears under a different aspect relative to the case of ballistic launch vehicles, in which the thrust depends very little on the flight conditions. In the latter case, it is preferable to traverse the dense layers of the atmosphere at low velocity so as to reduce the drag, which also permits using a structure that need not withstand excessive aerodynamic forces and thus can be of relatively light weight. Consequently, the flight path will deviate little from the vertical at low altitude.

Conversely, for an air-breathing vehicle, both thrust and drag originate from one and the same source. The specific impulse of the engine is no longer sufficient for characterizing the economy of propulsion. It is more important to make use of the corrected specific impulse which refers to the excess of engine thrust over vehicle drag. This corrected specific impulse naturally is much greater than that of rockets, provided that the size of the engine is sufficiently large. However, the greater the size the heavier will be the engine. In addition, a study of the equations of climb shows that it is almost always essential, from the viewpoint of fuel consumption, to climb at the greatest possible rate, i.e., at the maximum dynamic pressure that can be tolerated for a given altitude. This condition may lead to an increase in structural weight

of the aircraft, and one still will have to check whether this might not cancel the desired savings in fuel consumption.

A study of the climb path shows two critical zones for the propulsion; /6 these are the transonic passage and the evolution at high Mach number. Figure 2 gives the coefficients of drag and thrust as a function of the Mach number. The first zone is critical because of the low drag while the second zone is critical because of the deterioration of the engine thrust coefficient at high Mach numbers and the increase in induced drag. Two different engine sizes have been contemplated, corresponding to liftoff thrusts respectively equal to 30 and 40% of the liftoff weight. Two different laws of air rate of flow have been considered and bring out differences above Mach 3.8. The critical character of the two above-mentioned zones is even more clearly defined in Fig.3 which gives the correct specific impulses along the climb path.

To illustrate the role of selection of the flight path played in the mass distribution, Fig.4 gives the ratio of structural weight to all-up weight, for an aircraft of conventional design, as a function of the conventional velocity expressed in knots. At high Mach number, the mass of the thermal insulating devices or of the cooling installations must be taken into consideration. Let us return now to Fig.1. This diagram shows that the dominant limitations are those having to do with the engine, which means that the maximum Mach number of the mission must always be that still supportable by the engine itself. Obviously, thermal limitations pose the most serious problems.

Let us now discuss the type of air-breathing engine which we intend to use for propulsion of the first stage. This is a combination turbofan-ramjet, of which a schematic sketch is given in Fig.5. The unit is the result of work /7 done in our Company for more than 15 years, on combinations of turbofans and ramjets. These composites are familiar to everyone by now, and it is only necessary here to recall the outstanding success of the "Griffon" aircraft by Nord-Aviation. The compound engine of interest here consists basically of a coaxial arrangement of a turbofan unit with separate air bypasses, having an annular combustion chamber surrounding the rear portion of the turbine. The air inlet and the exhaust nozzle, both of variable geometry, are shared by the two types of engines. A post-combustion device can be installed in the primary bypass. Figure 6 gives a better view of the various operating modes of the unit. The flaps that regulate the output of the secondary bypass of the turbofan are of the variable type.

First case - in open position:

The secondary bypass air feeds the annular combustion chamber, so that the unit operates as a turbofan with combustion in both bypasses.

Second case - in closed position:

The secondary bypass air is eliminated and the combustion chamber is fed by the air that has circulated around the turbofan and thus acts as a ramjet combustion chamber. In this case, the turbine - depending on the value of the flight Mach - is either idling, windmilling, or even completely stopped.

Third case - in intermediate position:

This is the case of mixed or "combined" operation.

The secondary bypass air of the turbofan effectively mixes with the circulation flow in the siphon formed by the arrangement.

This time, it is the mixture that feeds the annular combustion chamber; this permits burning a mass of air greater than the discharge of the turbine.

The first variant is useful for the subsonic portion of the acceleration /8
phase as well as for passage through the sonic barrier; the second variant is used for operation at high Mach number, beyond the maximum Mach tolerated by the turbine and ranging between 2.5 and 3. The third variant is suitable for the intermediate velocities between transonic speed and Mach 2.5 - 3, depending on the capabilities of the turbine itself. It should be mentioned that during the subsonic return flight and in cruising flight, the engine can operate as a turbofan unit without heating or reheating, which makes it possible to obtain extremely low specific fuel consumptions.

Figures 7 and 8 show the performance of such a composite unit, as a function of the Mach number, where $\frac{F}{q}$ is the thrust divided by the dynamic pressure of flight, $\frac{F_o}{F_{oo}}$ is the static thrust at ground level divided by the static pressure. The curves give the specific consumption as a function of the ratio of these thrusts, for different Mach numbers.

The indicated values are those corresponding more or less to a composite unit equipped with an SNECMA TF 306 (or P & W TF 30) turbofan whose prototype development is proceeding independently of the various space programs and on which most of our present investigations are centered.

The use of a compound engine, corresponding to the principle described above, can be in question for various missions and offers no fundamental difficulty as long as the maximum Mach number remains below 4 or 4.5. Beyond these values, it becomes extremely difficult to overcome the effects of kinetic heating, even if the materials are selected with extreme care by making maximum use of insulation techniques and by utilizing the fuel as a cryogenic source. This brings up the subject of the need for a cryogenic fluid which, in addition to the properties of a good refrigerant, should also have that of a good fuel or oxidizer. This is the case for liquid hydrogen or liquid oxygen. Once its /9
use has been decided the actual application of a cryogenic fluid may assume various forms. Several combinations can be conceived; however, the complications involved are justified only if they are not subordinate to rapid progress in the technological domain. Therefore, the programs have been limited to the two following systems: the turbofan ramjet using hydrogen as fuel, and the turbofan ramjet using kerosene as fuel and equipped with liquid-oxygen injection to augment the thrust in critical cases. Specifically, the latter system has been the center of our attention. The system consists essentially in injecting oxygen into the combustion chamber so as to burn more kerosene and to increase

the ejected mass, which permits a considerable increase in thrust for the critical cases discussed above. Computation shows that this manner of using lox and kerosene is more economical than the conventional rocket, despite the fact that the pressure level in the chamber generally is higher than in the ramjet. This result is basically due to a lower level of dissociation. The use of liquid oxygen permits limiting the size of the engine and thus its weight to a value corresponding to about Mach 4. The weight gain obtained in this manner is sufficiently great to counterbalance the oxygen consumption. Figure 9 gives the performance data of this system, for different values of the ratio of mass of injected liquid oxygen to the mass of captured atmospheric oxygen.

In summation, it can be stated that such a system will be lighter in weight than a pure air-breathing system, that it will have a greater thrust at high Mach numbers and possibly also in the transonic regime, that its specific impulse at high Mach numbers will remain acceptable, that it will not lead to excessive weight increases of the basic turbofan ramjet unit, that it constitutes a cryogenic source, that the high density of the fluids used (kerosene and lox) permits the use of small-volume tanks, and finally that it offers extreme /10
flexibility of use in view of the fact that oxygen injection is applied only when necessary and in exactly the required amount.

Above, we have defined an air-breathing engine laid out for high Mach numbers, with corrected specific impulses considerably higher than those of conventional rockets. However, to profit fully from these advantages, one must be careful not to get lost in another field, namely, that of structure in view of the weight savings in the consummable fluids. Thus, our Company had become interested at an early date in studies of new structural formulas for application to the aerospace field. This involved mainly sandwich construction of thin corrugated steel sheets, of which Fig.10 shows various models. This type of structure is highly suitable for the fabrication of light-weight and rigid structural parts that are used mainly for variable-geometry air inlets, walls of diffusers and of annular ducts, flaps, and even elements of heat exchangers that form part of a turbofan ramjet composite. Our work on stainless steel structures has been progressed sufficiently for having arrived at numerous designs. As a typical example, Fig.11 shows a panel of the engine cowling to be used in the "Transall" aircraft. Figure 12 gives an intermediate-stage truncated-cone section of the satellite launch vehicle "Diamant". In both units, the elements are of the single-corrugation type. Figure 13 gives the AV intermediate stage of the Coralie stage of the European launch vehicle "Europa". This time, double-corrugation construction is used. One can see the numerous openings that were decided on post facto, which posed a few manufacturing problems whose solution necessitated the creation of a special welding tool. The methods of sandwich fabrication have continuously progressed toward the goal of full industrialization. Tests have shown that this type of structure has no basic flaw and /11
that, specifically, its behavior in the thermal and vibratory environment of rocket motors is satisfactory.

All above statements with respect to the problems of flight path, propulsion, and structure indicate the intimate connection existing between these factors; it is quite obvious that valid conclusions can be drawn without the necessity of tedious complete pre-project studies. An examination of Fig.1 shows that, above Mach 5, the difficulty of the problems increases rapidly;

therefore, to give an objective to the studies, it seems reasonable to roughly set a Mach 6 as maximum. This leaves to report what has been done already and what still remains to be done to reach this maximum, at least so far as the overall engine is concerned.

Let us discuss first the air inlet. In the aerodynamics sector, numerous tests have been conducted at a large number of research institutes up to the hypersonic regime, generally with fixed configurations but in a few cases also with variable-geometry configurations. Figure 14 shows the typical evolution of the cross section of the stream tube of air to be captured, as a function of the Mach number. Two laws have been considered here: one that limits the maximum intake cross section to that corresponding to Mach 3.7 and the other in which the limitation is that of Mach 4. It is obvious that, in the first case, the cross section must vary approximately at a ratio of 1:3 and, in the second case, from 1 to more than 4. Considerable difficulty exists in the mechanical realization of excessively large ratios and, in addition, the transonic drag may become prohibitive. Nevertheless, it seems possible to obtain ratios higher than those possible with Mach 3 aircraft such as the American SST or the B70, so long as a maximum intake cross section adapted to less than Mach 4 is used. The effect of the angle of attack permits a slight increase in the mass of /12 captured air at the end of the acceleration phase. Figure 15 gives the ratio of pressure recovery as a function of the Mach number, such as obtained by the American standard 5008-B, which we have used in our performance calculations. In general, the values were experimentally verified on fixed configurations.

We do not believe that major difficulties exist in satisfying the conditions of rate of flow and pressure ratio. Nevertheless, one must not disregard the large volume of work required for the technological development of the air inlet whose complexity is further increased by the necessity of boundary-layer removal by suction or pressure, at numerous points. It is no exaggeration to state that the volume of work will be greater than that of the work scheduled on the same subject with respect to the Mach 3 supersonic transport; however, it will remain within evaluable limits.

With respect to the compound engine itself, it can be stated that its feasibility up to Mach 4 has been established in the research as well as in the development stage. For a period of six years, numerous configurations of turbofan ramjet engines have been investigated by Nord-Aviation, specifically in connection with research contracts let by the US Air Force. Internal aerodynamics tests have made it possible to define the basic characteristics of the air ducts. Thus, the contours of the motor fairings and the forms of the diffuser walls have been established, ensuring a correct airflow without separation in all three operating modes scheduled for the machine (see Fig.6). It has also been possible to develop a system of variable flaps, which permits an efficient mixing and a homogeneous feeding of the annular combustion chamber in all cases under consideration. Finally, extensive experimental work has been done on a full-scale sector of the combustion chamber. This work was done on the test stands of the C.E.P. at Saclay, up to Mach 4 at 100,000 feet simulated altitude, under all flight configurations. The results have exceeded the expectations, /13 particularly with respect to the latitude of variation in fuel enrichment. What remains to be done in this particular field is mainly preparatory work for full-scale technological development based on off-the-shelf hardware, which well might

be the T.F. 306 engine. The modifications to be made on the turbofan itself will concern mainly the arrangement of accessories and of the oil-cooling cycle. Another task is to coordinate the regulation of fuel discharge from the combustion chamber with the operating parameters of the turbofan. The main portion of the work will center on integration of this modified turbofan with the annular combustion chamber in the complete engine. The problems of interaction of various engine types can be studied only experimentally; however, practical experience gained with the "Griffon" has shown that these problems are solvable.

Finally, the problems of the variable-geometry nozzle require a special effort, basically governed by the progress made in metallurgy. At present, we have already nozzles for afterburner-equipped jet engines at Mach 3; the temperatures encountered at Mach 5 will be of the same order of magnitude because of the use of liquid oxygen, but the length of the nozzles will be greater and the kinematics of variable geometry will be somewhat more complicated.

Beyond Mach 4 or 4.5, it is thus necessary to make use of liquid oxygen. The technology of lox is well developed at present, due to work done on bipropellant rockets. No doubt, there will be numerous adaptation problems, but it seems that all can be solved within the time required for development of the engine itself.

So far as the structures are concerned, we will have to continue our efforts toward use of superalloys and refractories, while still retaining - in most cases - the sandwich technique. Highly promising tests are presently in progress, based on the René 41 which permits maintenance at temperatures of 800°C, as well as on the basis of molybdenum and niobium alloys that allow a wall temperature of about 1300°C. Finally, for the walls of the combustion chamber, tantalum /14 has been considered, despite its high density, since it withstands temperatures of 1600°C.

We have initiated the study of various development programs to cover the main points mentioned above. On this basis, it seems reasonable to believe that the static testing of a combined turbofan ramjet engine, using oxygen injection, can be terminated within a period of about five years from now, which will have to be followed by another two years of flight testing, of which a rather large portion will be used also for final development of the vehicle itself.

To illustrate our above statements, Fig.16 gives a mockup of one of the variants of the space transport whose investigation is being continued in collaboration with our German colleagues of the ERNO group and, in France, with the SNECMA. The first stage is powered by turbofan ramjet units using oxygen injection at the end of the climb phase, as described above.

Overall, the characteristics of such a vehicle will be as follows:

Number of stages: 2 or 3
Total mass at liftoff: 200 tons
Mass insertable into low orbit: 3 tons
First stage with air-breathing engine
Total mass: 120 tons
Four turbofans

Total thrust at liftoff: 72 tons
Second stage, hydrogen/oxygen.

It is true that such a program seems ambitious and its realization will require a large budget which would have to be spread over about 10 or 12 years.

However, we hope to have shown that the realization of the engine itself /15 and the construction of the first stage will pose no problems whose "feasibility" has not already been proved.

So far as the upper stages are concerned, the problems will not differ greatly from those encountered in the development of hydrogen/oxygen rockets of the same thrust.

We believe that this constitutes an inter-European collaboration item, of a scope more far-reaching than any proposed up to now in the field of conventional ballistic launch vehicles.

In fact, no matter what Europe might do in the field of ballistic vehicles and no matter how great the ingenuity of its engineers in detail work might be, any effort in this direction will always reduce to a copying of American or Russian achievement, lagging two years behind, on a scale which will become increasingly lopsided with respect to dimensions and performance.

In contrast to this, only if Europe resolutely selects a work topic which, in our opinion, is no less ambitious, will it ever become possible to take the lead in technical progress along entirely novel lines, outside of the space race and concerning specifically the domain of hypersonic civil or military transport.

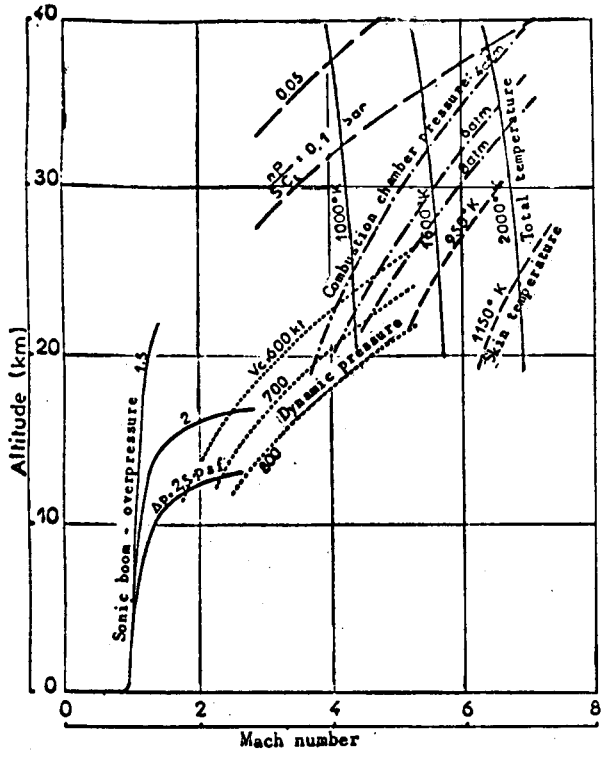

Fig.1 Limitations of the Climb Phase.

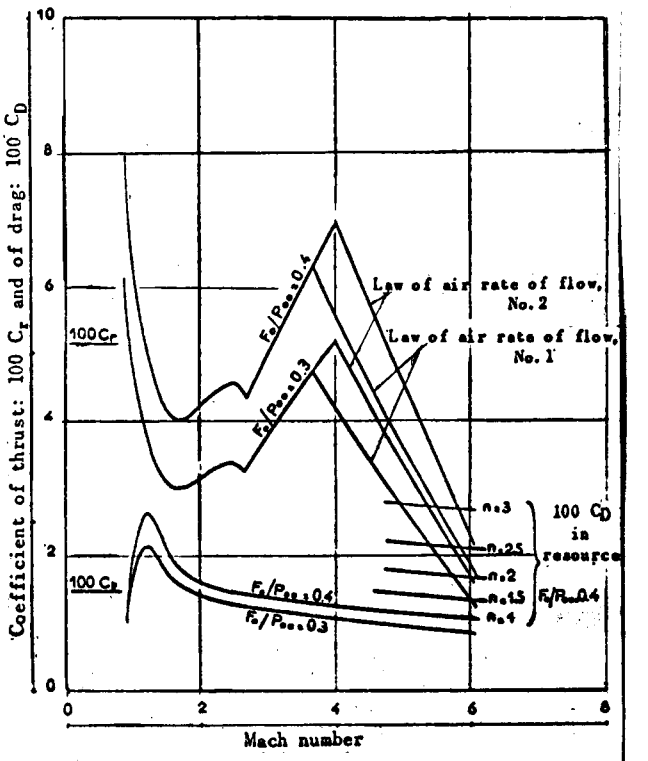

Fig.2 Coefficients of Drag and Thrust.

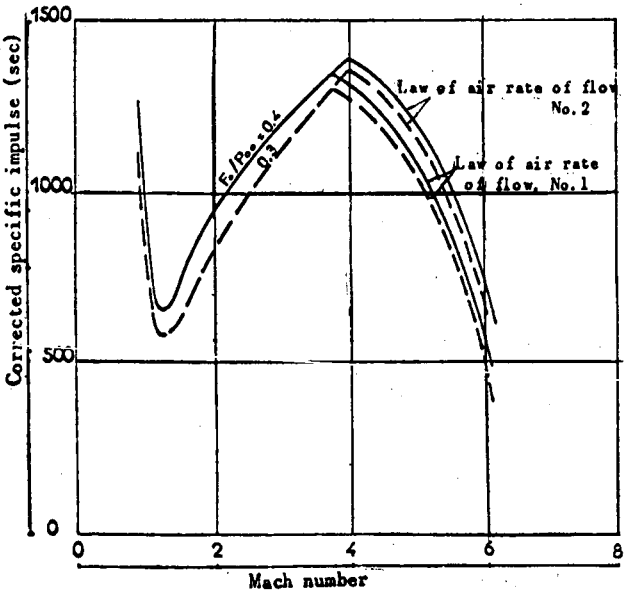

Fig.3 Corrected Specific Impulse.

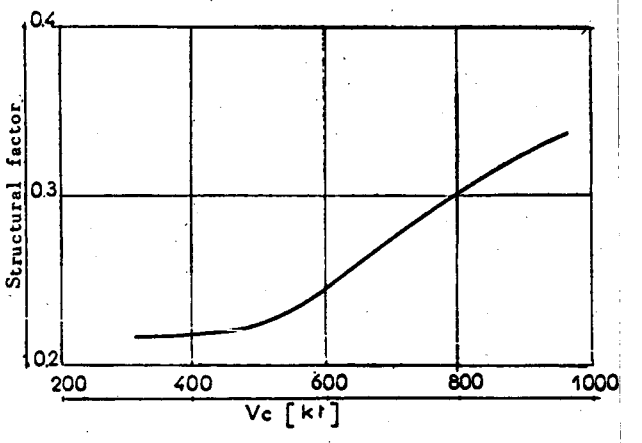

Fig.4 Evolution of the Structural Factor - Conventional Structure.

Combination of ramjet + turbofan

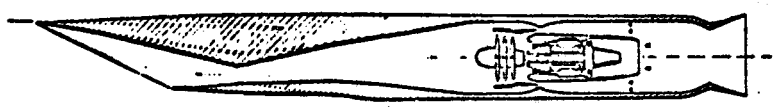

Fig.5 Schematic Section through the Engine with its Air Inlet.

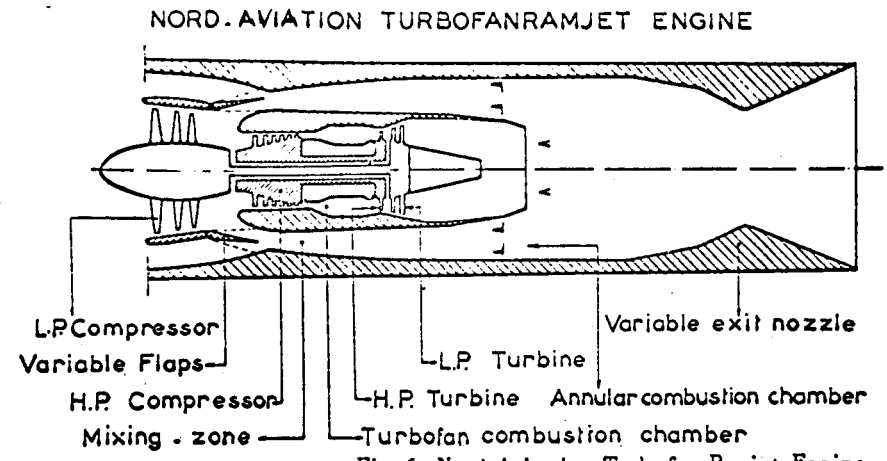

Fig.6 Nord-Aviation Turbofan Ramjet Engine.

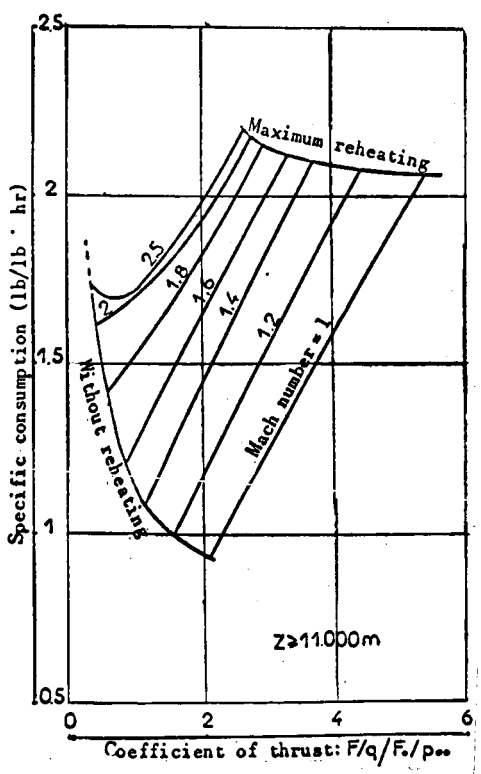

Fig.7 Reduced Performance Data.

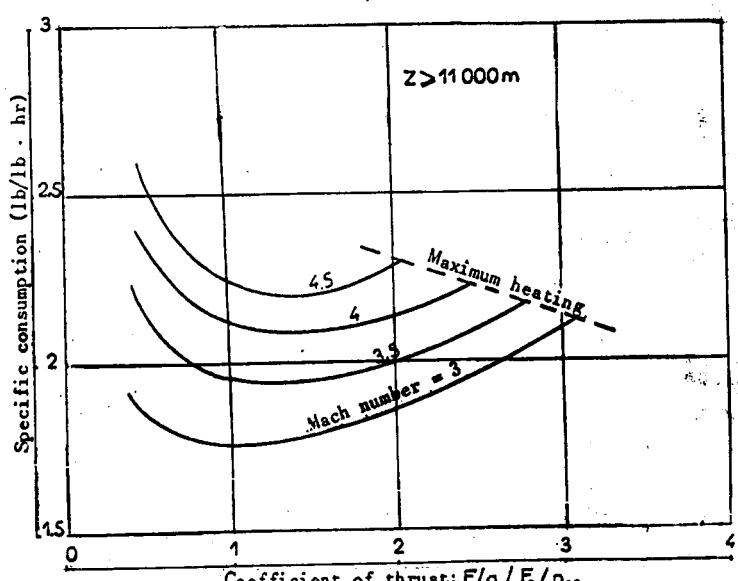

Fig.8 Reduced Performance Data.

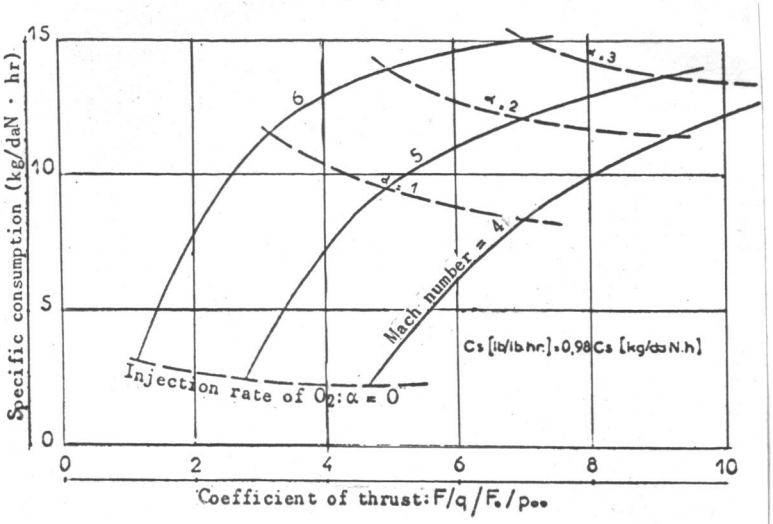

Fig. 9 Performance with Oxygen Injection.

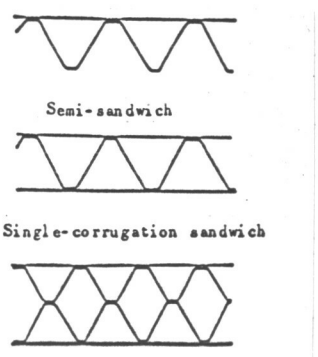

Fig. 10 Sandwich Structures.

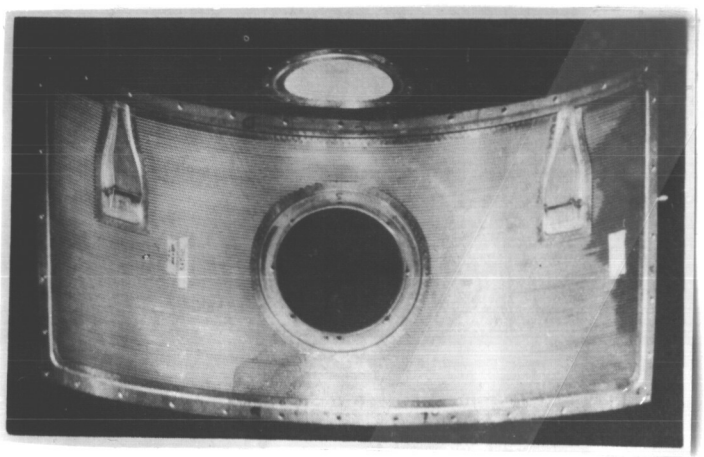

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Fig. 11 Panel of the Transall Engine Cowling.

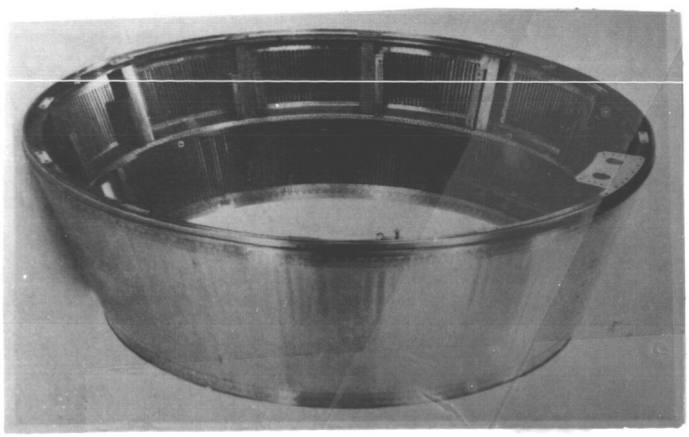

Fig. 12 Transonic Skirt AR of the Second Stage of the Diamant Rocket.

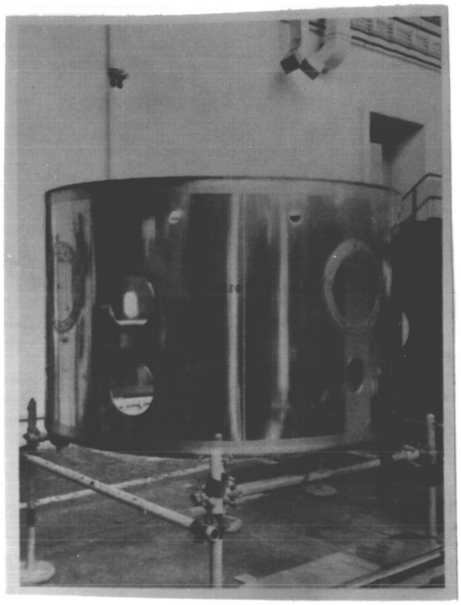

Fig. 13 Cylindrical Skirt AV of the Coralie Rocket.

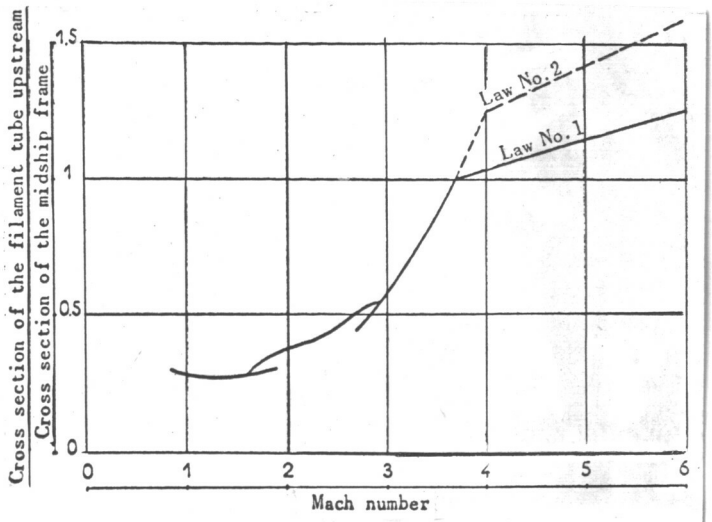

Fig. 14 Law of Variation in Rate of Flow of the Air Inlet.

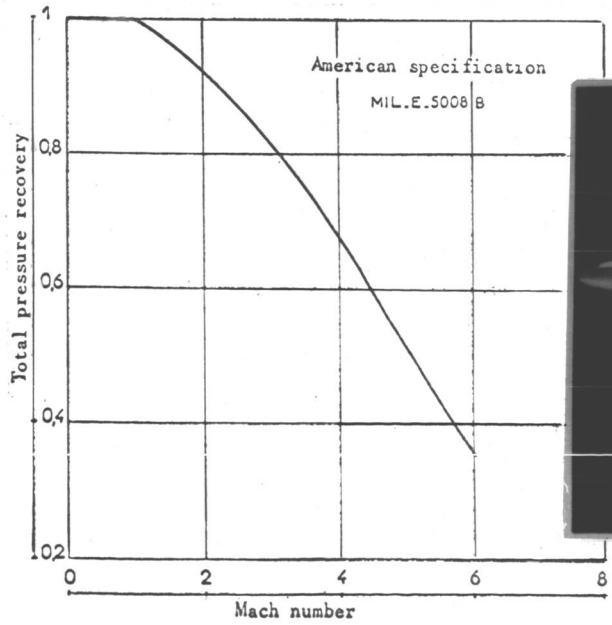

Fig. 15 Recovery of Total Pressure of the Air Inlet.

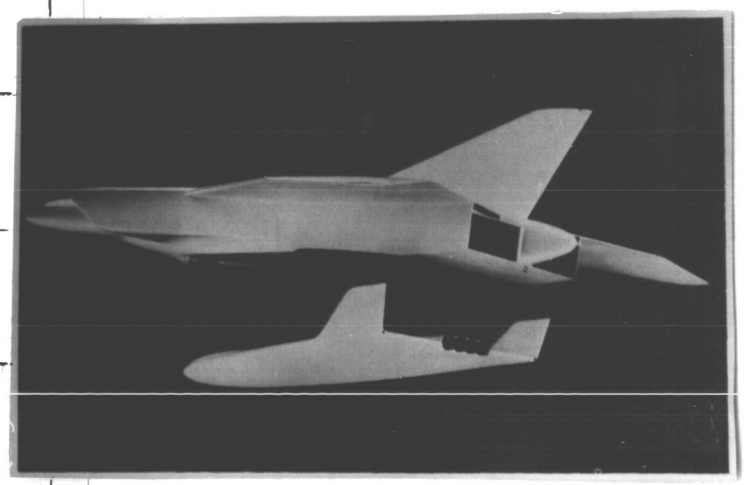

Fig. 16 Space Transport.

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